

Origin of the high-energy neutrino flux at IceCube

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Abstract

We discuss the different components in the astrophysical neutrino flux reaching the Earth and their possible contribution to the high-energy IceCube data. We show that the diffuse flux from cosmic ray interactions with gas in our galaxy implies just 2 events among the 54 event sample. We argue that the neutrino flux from cosmic ray interactions in the intergalactic (intracluster) space depends critically on the transport parameter δ describing the energy dependence in the diffusion coefficient of galactic cosmic rays. Our analysis motivates a $E^{-2.1}$ neutrino spectrum with a drop at PeV energies caused by a change in the cosmic-ray composition at $E > E_{\text{knee}}$. We show that this flux fits well the IceCube data, including the non-observation of the Glashow resonance at 6.3 PeV.

1 Introduction

The IceCube observatory has recently discovered a flux of TeV–PeV neutrinos whose origin is *not* atmospheric [1, 2]. In particular, four years of data include a total of 54 events of energy above 28 TeV. The spectrum, the track to shower ratio and the angular distribution of these events are consistent with a diffuse (isotropic) flux of astrophysical neutrinos harder than the atmospheric one. Where do these neutrinos come from?

Cosmic rays (CRs) are the key to understand any (atmospheric, galactic or extragalactic) neutrino fluxes, and it seems clear that IceCube’s discovery will have profound implications in CR physics. Moreover, the remarkable simplicity observed in the CR spectrum suggests that the high-energy neutrino flux may admit an equally simple description. Let us be more specific.

We observe that at energies below $E_{\text{knee}} = 10^{6.5}$ GeV CRs reaching the Earth are dominated by hydrogen and ^4He nuclei, having both species slightly different spectral index [3, 4]. In particular, we estimate

$$\Phi_p = 1.3 \left(\frac{E}{\text{GeV}} \right)^{-2.7} \text{ particles}/(\text{GeV cm}^2 \text{ s sr}) \quad (1)$$

and

$$\Phi_{\text{He}} = 0.54 \left(\frac{E}{\text{GeV}} \right)^{-2.6} \text{ particles}/(\text{GeV cm}^2 \text{ s sr}). \quad (2)$$

These expressions imply an all-nucleon flux $\Phi_N \approx 1.8 (E/\text{GeV})^{-2.7} (\text{GeV cm}^2 \text{ s sr})^{-1}$ and a similar number of protons and He nuclei at $E \approx 10$ TeV. Beyond E_{knee} up to $E_{\text{ankle}} = 10^{9.5}$ GeV the CR composition is uncertain, while the total flux becomes

$$\Phi = 330 \left(\frac{E}{\text{GeV}} \right)^{-3.0} \text{ particles}/(\text{GeV cm}^2 \text{ s sr}). \quad (3)$$

These spectral features, together with the almost perfect isotropy observed in the flux and the primary to secondary CR composition (the B/C ratio, the frequency of antimatter or of radioactive nuclei in CRs) can be accommodated within the following general scheme.

Galactic CRs are accelerated according to a power law $E^{-\alpha_0}$. The spectral index α that we see would then result after including propagation effects: CRs *diffuse* from the sources and stay trapped by galactic magnetic fields during a time proportional to $E^{-\delta}$. As a consequence $\alpha = \alpha_0 + \delta$, expressing that higher energy CRs are less frequent both because they are produced at a lower rate and because they propagate with a larger diffusion coefficient and leave our galaxy faster. The transport parameter δ is universal, in the sense that it is identical for CRs with the same rigidity $R = E/(Ze)$, and its value would be determined

by the magnetic fields in the interstellar (IS) medium. For example, a Kraichnan or a Kolmogorov spectrum of magnetic turbulences imply $\delta = 1/2$ or $1/3$, respectively [5]. The value of α_0 , in turn, may include some dependence with the CR composition; notice, in particular, that the difference in the proton and He spectral indices observed at $E < E_{\text{knee}}$ requires that $\alpha_0^p \approx \alpha_0^{\text{He}} + 0.1$. As for the spectral break observed at E_{knee} , it is thought to be associated to the sources rather than the transport: up to subleading effects [6] δ could be constant at all energies between 10 GeV (where the effects of the heliosphere become important) and a critical energy near E_{ankle} where the Larmor radius of CRs equals the maximum scale of the magnetic turbulences in the IS medium.

Although the basic parameters α_0 and δ can be fit using the observables mentioned above, there is some degree of degeneracy that allows for different possibilities [7, 8]. Take the CR flux below E_{knee} in Eqs. (1,2). The spectral index $\alpha = 2.6$ – 2.7 in the proton and He fluxes may result from $\alpha_0 = 2.1$ – 2.2 , which is expected from diffusive acceleration at supernova remnants, with $\delta = 0.5$. The data, however, could also be fit with a smaller diffusion parameter $\delta = 0.3$ – 0.4 if $\alpha_0 \approx 2.3$, which could be explained in models with significant CR reacceleration, or even with $\delta \approx 0.8$ in scenarios with strong convective winds if $\alpha_0 \approx 1.9$.

Here we will consider the simplest case, $\delta = 0.5$, and will discuss the implications of this value of δ on the spectrum of several components that define the high-energy neutrino flux reaching the Earth. We will estimate the number of events that each component could imply at IceCube and will propose one of them as the main origin of the observed signal.

2 Diffuse flux of galactic neutrinos

Astrophysical neutrinos of $E > 1$ GeV are non thermal, they appear always as secondary particles produced in the collisions of high-energy CRs with matter. Let us start considering the ones produced inside our own galaxy. CR collisions may take place mainly in two different environments: the interstellar (IS) medium where CRs are trapped for a long time (diffuse flux) and the dense regions at or near the acceleration sites (pointlike sources). The diffuse ν flux comes predominantly from directions along the galactic disk, whereas the local sources include pulsars and supernova remnants.

The diffuse flux of galactic neutrinos has been estimated by a number of authors [9–14]. It basically depends on three factors: (i) The CR density at each point in our galaxy, (ii) the gas density in the disk and the halo, and (iii) the neutrino yield in the collisions of the CRs with the IS gas (hydrogen and helium in a proportion near 3 to 1 in mass). We will take the approximate analytical expressions for the diffuse flux obtained in [14], where we

can find a detailed account of these three factors. At 10^3 – $10^{5.5}$ GeV this neutrino flux is [in $(\text{GeV cm}^2 \text{ sr s})^{-1}$]

$$\bar{\Phi}_\nu^{\text{gal}} = 3.7 \times 10^{-6} \left(\frac{E}{\text{GeV}} \right)^{-2.617} + 0.9 \times 10^{-6} \left(\frac{E}{\text{GeV}} \right)^{-2.538}, \quad (4)$$

where the two terms correspond to the contributions from the protons and the He nuclei in the CR flux, respectively, and the uncertainty is estimated at the 20%. Eq. (4) provides the total neutrino plus antineutrino flux averaged over all directions. The angular dependence (Φ_ν is 100 times stronger from the galactic disk than from high latitudes) can also be found in [14]. After oscillations the relative frequency of each flavor reads

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (1.13 : 1.07 : 0.99 : 0.91 : 0.99 : 0.91), \quad (5)$$

for the component in the flux coming from protons and

$$(\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (1.04 : 1.06 : 0.97 : 1.00 : 1.00 : 0.93). \quad (6)$$

for the neutrinos from He (or from any nucleus with a similar number of protons and neutrons).

At energies $E > 10^{6.5}$ GeV the expression in Eq. (4) is no longer valid and $\bar{\Phi}_\nu$ depends strongly on the CR composition beyond E_{knee} [14]:

$$\bar{\Phi}_\nu^{\text{gal}} = \begin{cases} 4.4 \times 10^{-4} \left(\frac{E}{\text{GeV}} \right)^{-2.918} & (100\% \text{ proton}), \\ 1.2 \times 10^{-4} \left(\frac{E}{\text{GeV}} \right)^{-2.938} & (100\% \text{ helium}), \\ 1.3 \times 10^{-5} \left(\frac{E}{\text{GeV}} \right)^{-2.974} & (100\% \text{ iron}). \end{cases} \quad (7)$$

We will use these expressions and will interpolate with a power law in the $10^{5.5}$ – $10^{6.5}$ GeV energy interval.

If compared with the atmospheric ν flux, the galactic flux in Eqs. (4,7) is small but not negligible. The atmospheric flux has two main components: the so called conventional neutrinos from light-meson decays (a detailed calculation can be found in [15]) and neutrinos from the prompt decay of forward charm [16]. In Fig. 1 we plot these fluxes and their dependence with the zenith angle θ at IceCube, where the declination is just $\theta - \pi/2$. At these energies the conventional flux contains muon and electron neutrinos in an approximate 30 to 1 proportion, whereas the ν flux from charm decays has a similar frequency of both flavors and a 2% of ν_τ . Conventional and charm neutrinos are described by different spectral indices (see Fig. 1), and although the first ones dominate the atmospheric flux up to $E \approx 250$ TeV, charm hadrons are the main source of electron neutrinos already at 10 TeV [16]. The atmospheric ν flux also has a strong dependence on the CR composition at $E > E_{\text{knee}}$ (it is

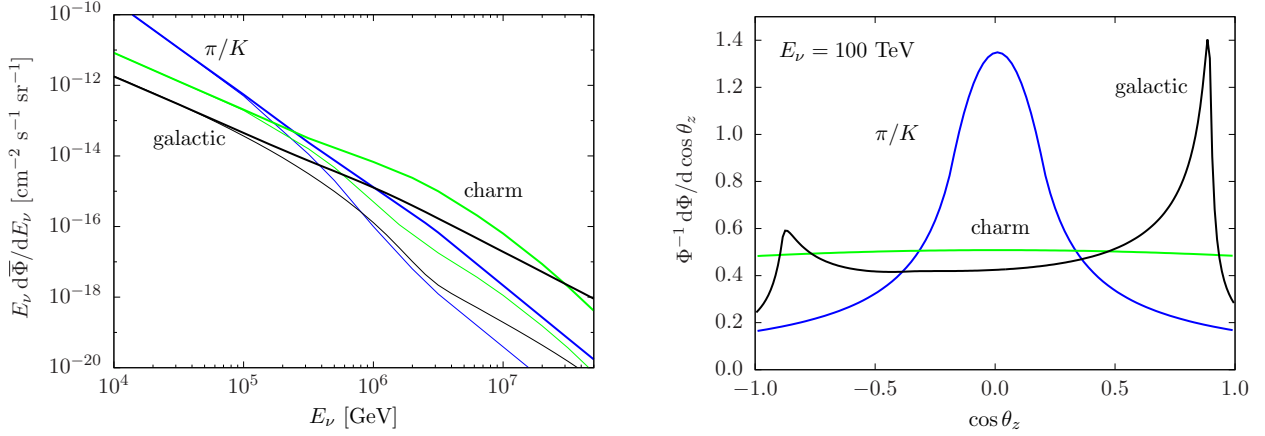


Figure 1: **Left.** Galactic and atmospheric fluxes (conventional and from charm decays); the thick (thin) lines correspond to a 100% proton (iron) CR composition at $E > E_{\text{knee}}$. **Right.** Normalized zenith angle distribution of these neutrino fluxes at IceCube ($\delta = \theta - \pi/2$).

proportional to $1/A$ [17, 18]). In the plot we see that the diffuse galactic flux is below the conventional one at $E < 1$ PeV, and it is just one fourth of the flux from charm decays at all IceCube energies.

We can readily estimate the number of events that these fluxes imply at IceCube and compare it with the data. In Table 1 we have defined three energy bins, three direction bins, and we have separated shower from track events [19]. Our estimate includes the attenuation by the Earth of the neutrino flux reaching IceCube from different zenith angles, the (energy and flavor-dependent) effective volume of the detector [1], and the veto due to the accompanying muon in downgoing atmospheric events [20]. Events in parentheses are not genuine neutrino interactions but atmospheric muons entering the detector from outside. The uncertainty in the atmospheric background estimated by IceCube [2] for these three energy bins is around 8.6, 1.1 and 0.1 events, respectively.

The comparison with the data reveals that there is an excess that is *(i)* more significant at higher energies and *(ii)* stronger for showers than for tracks and for down-going and near horizontal directions than for upgoing events. For example, there are a total of 14 events with a deposited energy between 100 and 300 TeV but just 2.9 ± 1.1 expected from atmospheric neutrinos. The table also reflects that galactic neutrinos only provide around 2 events among the 54 data sample. Our calculation of the galactic signal seems robust, as we reproduce within a 10% the signal estimated by IceCube for different astrophysical neutrino fluxes (their Fig. 3, page 49 in [2]). Although our result is significantly larger than the one obtained by other authors (*e.g.*, only 0.1 galactic events among IceCube’s three year

	Data	Atm	Gal	Data	Atm	Gal	Data	Atm	Gal	
Tracks	2	0.6+0.2	0.0	1	0.1+0.1	0.0	0	0.0+0.0	0.0	UPGOING (+20° < δ < +90°)
Showers	6	0.2+1.0	0.2	1	0.0+0.5	0.1	0	0.0+0.1	0.0	
Tracks	3	(3)+2.8+0.3	0.1	1	0.8+0.2	0.1	0	0.1+0.0	0.0	HORIZONTAL (−20° < δ < +20°)
Showers	8	(1)+1.1+1.4	0.3	2	0.2+0.8	0.2	1	0.0+0.2	0.1	
Tracks	7	(6.4)+0.0+0.0	0.1	0	0.0+0.0	0.1	1	0.0+0.0	0.0	DOWNGOING (−90° < δ < −20°)
Showers	9	(2.2)+0.1+0.6	0.4	9	0.0+0.1	0.3	3	0.0+0.0	0.1	
Total	35	(12.6)+4.9+3.4	1.1	14	1.2+1.7	0.9	5	0.1+0.3	0.3	
	30–100 TeV			100–300 TeV			300–3000 TeV			

Table 1: Number of events at IceCube implied by the atmospheric neutrino flux (conventional plus charm) and by the diffuse galactic neutrino flux. We have assumed a pure He composition in the CR flux at $E > E_{\text{knee}}$. Events in parentheses correspond to atmospheric muons entering the detector from outside.

data [12]), it is still unable to explain the high-energy IceCube excess.

3 Other components in the neutrino flux

Let us go back to the simple scheme for the galactic CR flux outlined in Section 1, with a spectral index $\alpha^A = \alpha_0^A + \delta$ for each species A . It is important to notice that, up to collisions and energy loss, the effects of the propagation will be identical for CRs with the same rigidity (same value of E/Z). A He nucleus ($Z = 2$) of energy E will describe exactly the same trajectory through the galaxy as a proton of energy $E/2$. This implies a relationship between the fluxes $\Phi_{p,\text{He}}(E)$ that we see at the Earth and the production rate $I_{p,\text{He}}(E)$ of each species at the sources:

$$\begin{aligned}\Phi_p &= \left(n (E/1)^{-0.5}\right) \times I_p \\ \Phi_{\text{He}} &= \left(n (E/2)^{-0.5}\right) \times I_{\text{He}},\end{aligned}\tag{8}$$

where the factor multiplying $I_A(E)$ includes the overall normalization n and the propagation effects for $\delta = 0.5$. Therefore, taking the fluxes in Eqs. (1,2) we obtain that at $E < E_{\text{knee}}$ the relative production rate of CRs by our galaxy is

$$\begin{aligned}I_p &= C E^{-2.2} \\ I_{\text{He}} &= 0.29 C E^{-2.1}.\end{aligned}\tag{9}$$

Notice that within this scheme CRs would stay confined in the galaxy for a period of order

$$\tau_G \approx 10^7 \text{ years} \times \left(\frac{E}{Z \times 10 \text{ GeV}} \right)^{-0.5}. \quad (10)$$

We then assume a steady state, *i.e.*, the number of CRs leaving the galaxy is similar to the number of CRs accelerated at the sources. This means that at energies below E_{knee} our galaxy is emitting protons and He nuclei at the rate given in Eq. (9). Once emitted, these CRs will stay inside the cluster and supercluster –generically, the intergalactic (IG) medium– containing our galaxy for a time that may be larger than the age of the universe [23, 24].

A similar argument applied to the CR flux at $E > E_{\text{knee}}$ in Eq. (3) implies a galactic production/emission rate

$$I_A = \frac{254}{\sqrt{Z}} C E^{-2.5}, \quad (11)$$

where Z is the corresponding atomic number of the CRs dominating the galactic flux at these energies. Our basic statement in Eqs. (9,11) is that the spectral index and the relative composition of the CRs emitted by our galaxy into the IG medium are correlated with the ones we see reaching the Earth, and that this correlation depends on a single transport parameter δ that, in the simple scenario under consideration, takes the value $\delta = 0.5$.

Let us now assume that galaxies (the supernova remnants and pulsars inside them) are the main source of CRs of energy up to 10^8 GeV, and that ours is an *average* galaxy. CRs can then be found (*i*) inside the galaxies (including ours), where they exhibit the spectrum and composition in Eqs. (1–3), and (*ii*) in the IG space, where they appear with the spectrum and the composition in Eqs. (9,11). The interactions of these two types of CRs with the gas in the medium where they propagate will produce TeV–PeV neutrinos. Therefore, in the astrophysical neutrino flux discovered by IceCube we may consider the relative weight of the following three components:

- Neutrinos from CR interactions with the IS matter in our own galaxy. This component, Φ_ν^{gal} , has been discussed in the previous section, and it is way too low to account for the number of events detected at IceCube. In addition, these neutrinos are concentrated near the galactic plane.
- Neutrinos from the same type of interactions but in other galaxies. As discussed above, if both the accelerators and the spectrum of magnetic turbulences are universal we may expect that the IS medium in other galaxies will confine CRs with the same spectrum and relative composition as in ours, given in Eqs. (1–3). Collisions with the gas there will then produce a neutrino flux from all galaxies, Φ_ν^{AG} , proportional to

the one in Eqs. (4,7). Such flux will be more isotropic than the one discussed in the previous section, but its $\approx E^{-2.6}$ spectrum seems too steep to account for a significant fraction of the IceCube events. In particular, it has been shown [21] (see also [9]) that the neutrino flux would come together with a 10–100 GeV diffuse gamma-ray flux inconsistent with Fermi-LAT data [22].

- Neutrinos from interactions of CRs with extragalactic gas [23–27]. As mentioned before, the CRs producing this IG neutrino flux Φ_ν^{IG} are steadily emitted by all the galaxies with the spectrum and composition in Eqs. (9,11). In the intracluster space these CRs will face a gas density typically 10^{-4} times smaller than the one inside the parent galaxy, but the time they spend there may be 10^{-5} times larger, resulting into a larger column density. In addition, while inside galaxies CRs are in a steady state, in the IG medium the total number of CRs grows with time.

In the next sections we will calculate Φ_ν^{IG} up to an overall normalization factor and will show that their spectrum may provide a good fit of the high-energy IceCube data, including the non-observation of the Glashow resonance at 6.3 PeV.

4 Diffuse flux of intergalactic neutrinos

Our starting point is a CR number density in IG space with the spectrum and the relative composition given by Eqs. (9,11). Notice that an isotropic flux Φ_A of (relativistic) CRs type A would be simply related to the number density n_A by $\Phi_A = n_A c/(4\pi)$. Let us assume that the average gas density in the IG medium is $\bar{\rho}_{\text{IG}}$, with a (1:3) He to H ratio. The neutrino flux reaching the Earth from CR collisions with the gas along the line of sight is then [14]

$$\bar{\Phi}_\nu(E) = R \bar{\rho}_{\text{IG}} \sum_A \frac{F_A}{m_p} \int_0^1 dx \sigma_{Ap}(E/x) \bar{\Phi}_A^{\text{IG}}(E/x) x^{-1} f_A^\nu(x, E/x). \quad (12)$$

where R is the maximum distance* in our supercluster and beyond, A runs over the different species in the CR flux, $f_{Ap}^\nu(x, E')$ is the yield of neutrinos carrying a fraction x of the incident energy produced in Ap collisions, and F_A takes into account the mixed H/He composition of the IG gas ($F_p \approx 0.92$, $F_{\text{He}} \approx 0.90$ and $F_{\text{Fe}} \approx 0.86$ [14]). This expression gets simplified if one neglects the energy dependence of the yields and takes an unbroken power law both for the intergalactic CR flux [$\bar{\Phi}_A^{\text{IG}}(E) = n_A I_A = n_A E^{-\alpha_A}$, with I_A given in Eqs. (9,11)] and for

*We neglect the redshift in the contribution to the neutrino flux from distant clusters.

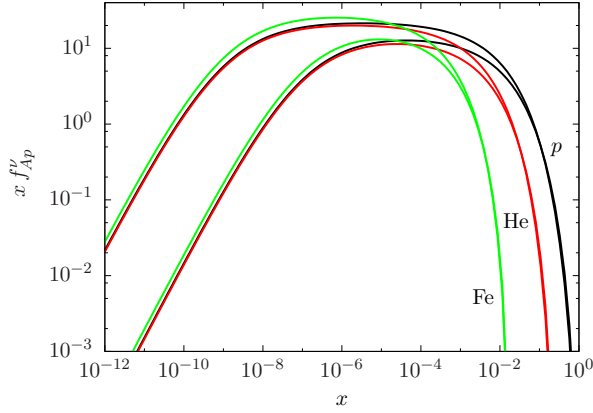


Figure 2: Total neutrino yield (ν and $\bar{\nu}$ of all flavors) $f_A^\nu(x, E)$ from $A = \text{proton, helium and iron}$ collisions with a proton at rest at $E = 10^6, 10^8$ GeV [14].

the cross section [$\sigma_{Ap}(E) = \sigma_{Ap}^0 E^{\beta_A}$]:

$$\bar{\Phi}_\nu^{\text{IG}}(E) = R \bar{\rho}_{\text{IG}} \sum_A \frac{F_A \sigma_{Ap}^0 n_A}{m_p} Z_A^\nu E^{-(\alpha_A - \beta_A)}, \quad (13)$$

being Z_A^ν the order- $(\alpha_A - \beta_A - 1)$ moment of the yield,

$$Z_A^\nu = \int_0^1 dx x^{\alpha_A - \beta_A - 1} f_A^\nu(x). \quad (14)$$

We see that the energy dependence of the cross sections will slightly change the spectral index of the IG neutrino flux from α_A to $\alpha_A - \beta_A$. In pp collisions we have $\beta_p = 0.082$ and $\sigma_{pp}^0 = 17.7$ mb, whereas in $\text{He}p$ and $\text{Fe}p$ collisions $\beta_{\text{He}} = 0.062$, $\sigma_{\text{He}p}^0 = 60.5$ mb, $\beta_{\text{Fe}} = 0.026$ and $\sigma_{\text{Fe}p}^0 = 551$ mb. Taking the yields from [14] and encapsulating the unknowns in a single normalization factor N , at $E < 10^{5.5}$ GeV we obtain

$$\bar{\Phi}_\nu^{\text{IG}} = 2.8 N E^{-2.12} + 1.0 N E^{-2.04}, \quad (15)$$

where the two terms come from the proton and the He contributions, respectively. At neutrino energies $E > 10^{6.5}$ GeV we find

$$\bar{\Phi}_\nu^{\text{IG}} = \begin{cases} 290 N E^{-2.42} & (100\% \text{ proton}), \\ 106 N E^{-2.44} & (100\% \text{ helium}), \\ 11 N E^{-2.47} & (100\% \text{ iron}). \end{cases} \quad (16)$$

The large uncertainty in $\bar{\Phi}_\nu^{\text{IG}}$ is related to the CR composition: its origin is the Z -moment of the neutrino yield, which is much smaller for heavy nuclei than for protons (see Fig. 2). If primary CRs above E_{knee} were mostly protons, then $\bar{\Phi}_\nu^{\text{IG}}$ would be 3.8 times larger than

	30–100 TeV	0.1–0.3 PeV	0.3–3 PeV	3–10 PeV
Excess	13.0±8.6	10.2±1.1	4.3±0.1	0
$E^{-2.0}$	4.7	6.4	8.1	3.2
$E^{-2.58}$	11.5	9.3	5.2	0.7
IG	7.6	9.3	5.2	0.4
AG	14.0	11.0	3.5	0.1

Table 2: Total number of events for 1347 days at IceCube implied by the four fluxes discussed in the text together with the excess deduced from Table 1.

if they are pure helium, but this neutrino flux could also be a factor of 0.056 smaller if CRs were 100% iron.

In order to simplify our analysis, beyond E_{knee} we will consider the IG flux

$$\bar{\Phi}_{\nu}^{\text{IG}} = a N E^{-2.44} \quad (17)$$

with $6 < a < 400$, and we will use a power law to interpolate between this flux and the one in Eq. (15) at $E < 10^{5.5}$ GeV. Notice that the same value of a may result from different CR compositions; for example, $a = 106$ could correspond to 100% He or to 25% proton plus 75% iron. In the next section we will fit the high-energy IceCube data with the parameters N and a in this neutrino flux.

5 Fit of the high-energy IceCube data

Let us take the average IG flux obtained in the previous section to be isotropic.[†] In the first row of Table 2 we write the IceCube excess in each energy bin, *i.e.*, the difference between the data and the sum of the atmospheric and the galactic events given in Table 1, including IceCube’s estimate of the background uncertainty. In the second and the third rows we give the number of events predicted by unbroken power laws with spectral indices 2.0 and 2.58, respectively. The first case was proposed by IceCube after three years of observations, whereas the flux proportional to $E^{-2.58}$ provides their best fit once the more recent data are added. In the fourth and fifth rows of Table 2 we give the number of events predicted by the IG flux Φ_{ν}^{IG} with $a = 106$ and by the all-galaxies flux Φ_{ν}^{AG} , which basically consists of the galactic flux in Eqs. (4,7) but isotropic and with an arbitrary normalization.

The normalization of each astrophysical flux has been fixed so that they reproduce the

[†]The flux could actually be modulated by the large-scale structure around our galaxy.

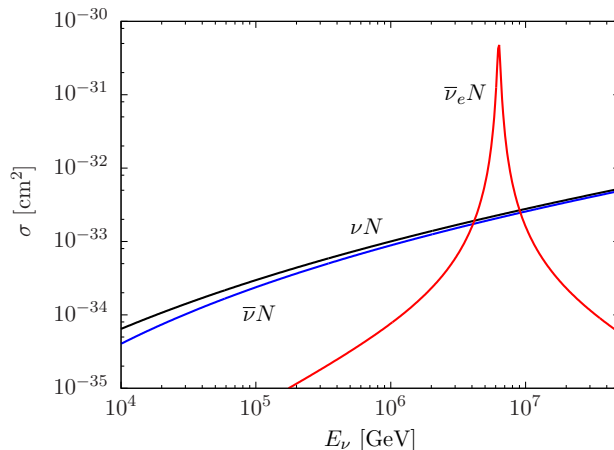


Figure 3: Total νN , $\bar{\nu} N$ and $\bar{\nu}_e e$ cross sections.

total IceCube excess at 100 TeV–3 PeV (*i.e.*, the sum of the two high energy bins in Table 1). The flux Φ_ν^{AG} would imply a too strong gamma-ray signal [9, 21] at Fermi-LAT [22], whereas the one proportional to $E^{-2.58}$ would require a mechanism that absorbs the gammas created together with the neutrinos [28].

Notice that in Table 2 we have added a fourth energy bin, 3–10 PeV, which provides an important piece of information in order to decide about the goodness of the fits. At these energies electron antineutrinos could reveal the Glashow resonance through collisions with electrons:

$$\bar{\nu}_e e \rightarrow W^- \rightarrow q \bar{q}, \ell \bar{\nu}_\ell \quad (18)$$

In Fig. 3 we show that at $E = (6.3 \pm 2.0)$ PeV the cross section for this process [29] goes well above $\sigma(\nu N)$ [30]. Since the IceCube target has 10 electrons per 18 nucleons and the $\bar{\nu}_e$ frequency in the IG neutrino flux is almost exactly 1:6 [see Eq. (6)], the Glashow resonance will clearly have an impact on the fit. Notice also that when the W decays hadronically (with a 67.6% branching ratio) all the neutrino energy E_ν will be deposited in the ice, while in leptonic decays (32.4% of the times) the charged lepton will take an energy between 0 and E_ν with an average value of $0.33 E_\nu$ [29].

We find that the $E^{-2.0}$ flux implies 3.2 events beyond 3 PeV, while all the other fluxes may fit the data while predicting less than one event in that bin. Therefore, the non-observation of the Glashow resonance after four years of data disfavors the harder $E^{-2.0}$ flux initially proposed by IceCube. The physically motivated flux Φ_ν^{IG} has a similar spectral index at lower energies [see Eq. (15)], however, a possible break caused by a change in the CR composition at E_{knee} may define an acceptable possibility. Indeed, although the amount of IceCube data

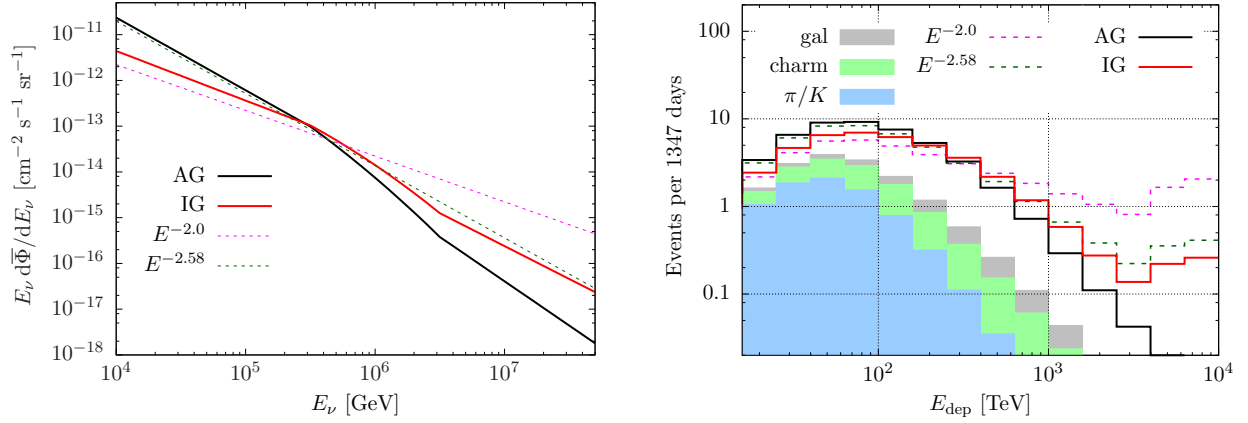


Figure 4: **Left.** Different components in the neutrino flux reaching the Earth. The IG, G, AG and atmospheric fluxes correspond to a dominant helium composition in the CR flux at $E > E_{\text{knee}}$. **Right.** Event distribution implied at IceCube (1347 days).

does not provide a significant discriminant among the different possibilities, the presence of the knee in the CR spectrum implies that we should *not* expect an unbroken power law in the neutrino flux at TeV–PeV energies.

In Fig. 4 we plot these astrophysical ν fluxes together with the total number of events that they imply at all IceCube energies. For comparison, the normalization of the atmospheric and galactic neutrinos fluxes in Fig. 1 reads

$$\begin{aligned}\bar{\Phi}_{\nu}^{\pi/K}(100 \text{ TeV}) &= 5.1 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}, \\ \bar{\Phi}_{\nu}^{\text{charm}}(100 \text{ TeV}) &= 1.9 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}, \\ \bar{\Phi}_{\nu}^{\text{gal}}(100 \text{ TeV}) &= 4.9 \times 10^{-19} (\text{GeV cm}^2 \text{ sr s})^{-1}.\end{aligned}\tag{19}$$

whereas the four fluxes in Fig. 4 have been normalized to

$$\begin{aligned}\bar{\Phi}_{\nu}^{(2.0)}(100 \text{ TeV}) &= 2.2 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}, \\ \bar{\Phi}_{\nu}^{(2.58)}(100 \text{ TeV}) &= 5.2 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}, \\ \bar{\Phi}_{\nu}^{\text{IG}}(100 \text{ TeV}) &= 3.6 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}, \\ \bar{\Phi}_{\nu}^{\text{AG}}(100 \text{ TeV}) &= 6.1 \times 10^{-18} (\text{GeV cm}^2 \text{ sr s})^{-1}.\end{aligned}\tag{20}$$

6 Summary and discussion

High energy neutrinos can only be produced in the collisions of charged CRs. It seems then clear that the discovery at IceCube of an astrophysical neutrino flux will have implications

in our understanding of high energy CRs. In particular, a higher statistics should establish the spectral index of this flux at $E \lesssim 1$ PeV and, most important, the presence or not of the Glashow resonance at $E \approx 6.3$ PeV. We have shown that these two observations will provide clear hints about the spectrum and the composition of the parent CRs, which in turn relate to the environment where the neutrinos have been produced.

Galactic CRs are described by a spectrum $\approx E^{-\alpha}$ that is steeper than the one they have at the sources: $\alpha_0 = \alpha - \delta$ with $\delta = 0.5$ in the simplest scenario. The neutrinos produced in their collisions will inherit the spectral index of the parent CR flux. If the main source of the IceCube neutrinos were the collisions of CRs *inside* galaxies, then their spectral index would be 2.6 at $E < 10^{5.5}$ GeV and around 2.9 at higher energies. A few 1–2 PeV events at IceCube from such steep flux would then be correlated with a too large diffuse gamma-ray flux at 0.1–100 GeV [9, 21]. Once CRs leave into the IG space, however, their spectral index should be similar to the one they have at the sources. In Eq. (15) we provide a two-component (from proton and He collisions) IG neutrino flux with a spectral index near 2.1. Such a hard spectrum, if unbroken, should have already revealed the Glashow resonance. We have shown, however, that if the CR knee brings a change in the composition towards heavier nuclei then the secondary neutrino flux may experience a sudden drop at $E > 1$ PeV. Therefore, the observation (or not) of the Glashow resonance will provide important information about the CR composition at these energies.

As a viable possibility, we have studied the implications at IceCube of the IG neutrino flux that may appear if CRs above E_{knee} are dominated by He ($a = 106$ in Eq. (17)). Our results are summarized in Table 2. We see that, normalizing the neutrino flux so that the total number of events in the two high energy bins matches the experimental excess, this single component Φ_{ν}^{IG} provides a good fit of all the data. We find that the (much steeper) galactic diffuse flux Φ_{ν}^{gal} contributes with just two events in the IceCube sample, a number that is significantly larger than previous estimates by other authors. Within our scheme, a pure proton composition above the CR knee is disfavored as Φ_{ν}^{IG} would imply around 2 events of $E > 3$ PeV.

Our analysis depends basically on the transport parameter δ . The value $\delta = 0.5$ that we have considered is consistent with a Kraichnan spectrum of magnetic turbulences and diffusive shock acceleration at supernova remnants, although other possibilities could be accommodated. Therefore, we think that the astrophysical neutrino flux discovered by IceCube, once it is fully characterized, will provide very valuable information that will help to complete the CR puzzle.

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References

- [1] M. G. Aartsen *et al.* [IceCube Collaboration], Science **342** (2013) 1242856; Phys. Rev. Lett. **113** (2014) 101101.
- [2] M. G. Aartsen *et al.* [IceCube Collaboration], *Proceedings of the 34th ICRC*, arXiv:1510.05223 [astro-ph.HE].
- [3] M. Boezio and E. Mocchiutti, Astropart. Phys. **39-40** (2012) 95.
- [4] Y. S. Yoon *et al.*, Astrophys. J. **728** (2011) 122.
- [5] V. S. Ptuskin, I. V. Moskalenko, F. C. Jones, A. W. Strong and V. N. Zirakashvili, Astrophys. J. **642** (2006) 902; V. Ptuskin, J. Phys. Conf. Ser. **47** (2006) 113.
- [6] P. Blasi, E. Amato and P. D. Serpico, Phys. Rev. Lett. **109** (2012) 061101.
- [7] D. Maurin, A. Putze and L. Derome, Astron. Astrophys. **516** (2010) A67.
- [8] G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso and L. Maccione, Astropart. Phys. **34** (2010) 274.
- [9] F. W. Stecker, Astrophys. J. **228** (1979) 919.
- [10] V. S. Berezinsky, T. K. Gaisser, F. Halzen and T. Stanev, Astropart. Phys. **1** (1993) 281.
- [11] C. Evoli, D. Grasso and L. Maccione, JCAP **0706** (2007) 003.
- [12] J. C. Joshi, W. Winter and N. Gupta, Mon. Not. Roy. Astron. Soc. **439** (2014) no.4, 3414 Erratum: [Mon. Not. Roy. Astron. Soc. **446** (2014) no.1, 892].
- [13] M. Ahlers and K. Murase, Phys. Rev. D **90** (2014) no.2, 023010.
- [14] J. M. Carceller and M. Masip, JCAP **1703** (2017) no.03, 013.

- [15] P. Lipari, *Astropart. Phys.* **1** (1993) 195.
- [16] F. Halzen and L. Wille, *Phys. Rev. D* **94** (2016) 014014.
- [17] P. Lipari, “Establishing the astrophysical origin of a signal in a neutrino telescope,” arXiv:1308.2086 [astro-ph.HE].
- [18] T. K. Gaisser, *EPJ Web Conf.* **52** (2013) 09004.
- [19] J. I. Illana, M. Masip and D. Meloni, *Astropart. Phys.* **65** (2015) 64.
- [20] M. G. Aartsen *et al.* [IceCube Collaboration], *Phys. Rev. D* **91** (2015) 022001.
- [21] K. Murase, M. Ahlers and B. C. Lacki, *Phys. Rev. D* **88** (2013) no.12, 121301.
- [22] A. A. Abdo *et al.* [Fermi-LAT Collaboration], *Phys. Rev. Lett.* **104** (2010) 101101.
- [23] V. S. Berezinsky, P. Blasi and V. S. Ptuskin, *Astrophys. J.* **487** (1997) 529.
- [24] D. Harari, S. Mollerach and E. Roulet, *JCAP* **1608** (2016) no.08, 010.
- [25] D. De Marco, P. Blasi, P. Hansen and T. Stanev, *Phys. Rev. D* **73** (2006) 043004.
- [26] K. Murase and J. F. Beacom, *JCAP* **1302** (2013) 028.
- [27] F. Zandanel, I. Tamborra, S. Gabici and S. Ando, *Astron. Astrophys.* **578** (2015) A32.
- [28] K. Murase, D. Guetta and M. Ahlers, *Phys. Rev. Lett.* **116** (2016) no.7, 071101.
- [29] A. Bhattacharya, R. Gandhi, W. Rodejohann and A. Watanabe, *JCAP* **1110** (2011) 017.
- [30] A. Connolly, R. S. Thorne and D. Waters, *Phys. Rev. D* **83** (2011) 113009.